Building Blocks for Transport-Class Hybrid and Turboelectric Vehicles

Amy Jankovsky
Cheryl Bowman
Ralph Jansen

Hybrid Gas Electric Propulsion

NASA Glenn Research Center
Cleveland, Ohio

Advanced Air Transport Technology Project
Advanced Air Vehicles Program

NASA's Motivation for Exploring Electrified Propulsion

Explore use of alternative propulsion to *reduce carbon use, noise and emissions in US airspace*

- Promise of cleaner energy
- Potential for vehicle system efficiency gains (use less energy)
- Seek to leverage advances in other transportation and energy sectors
- Address aviation-unique challenges (e.g. weight, altitude)
- Recognize potential for early learning and impact on smaller or shorter range aircraft

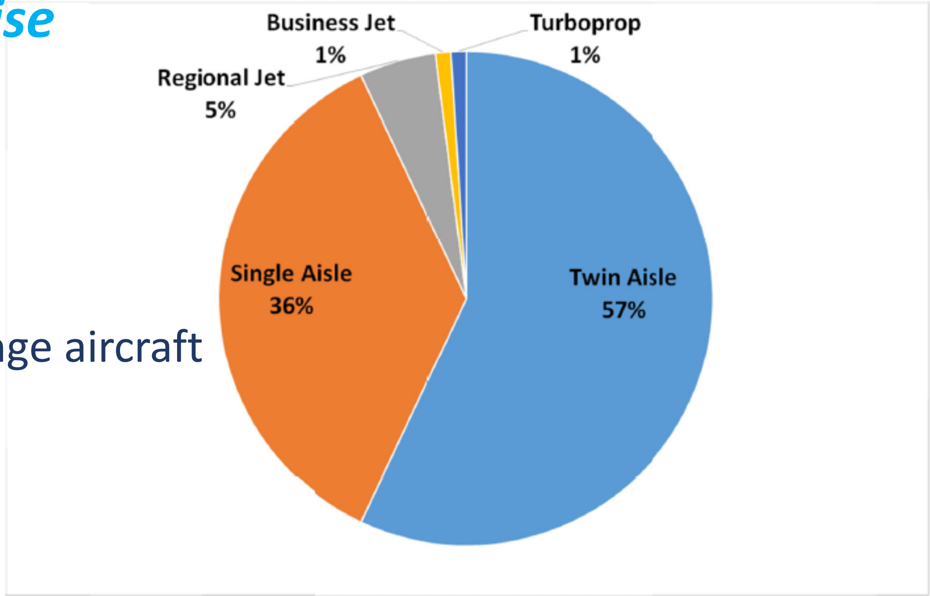
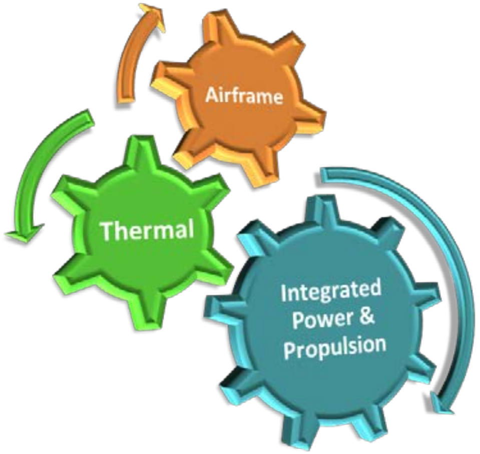


FIGURE 1.1 Global civil aviation fuel consumption. SOURCE: Data from B. Yutko and J. Hansman, 2011, *Approaches to Representing Aircraft Fuel Efficiency Performance for the Purpose of a Commercial Aircraft Certification Standard*, MIT International Center for Air Transportation, Cambridge, Mass.



Significant Challenges Remain

- Added weight and loss of Electrical Systems
- Can require Energy Storage advances
- How to integrate?
- How to control? How to fly?
- How to certify and maintain safety?

The solutions will be SYSTEMS-level

Different Use Cases Lead to Different Vehicles

On Demand Mobility
Small Plane Focus

All Electric, Hybrid Electric, Distributed Propulsion

Enable New Aero Efficiencies

Power Sharing

Distributed Thrust Control

Certification Trailblazing

Energy & Cost Efficient, Short Range Aviation

Low Carbon Propulsion
Transport-Class Focus

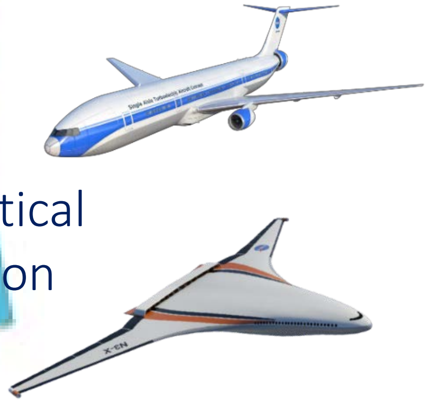
Turbo Electric, Distributed Propulsion

Enable New Aero Efficiencies

High Efficiency Power Distribution

Power Rich Optimization

Non-flight Critical First Application



Energy & Cost Efficient, Transport Aviation

Concepts for Distributed Electric Propulsion, Commuters

9 Passenger Concept

Small Commuter Concept

- 9 passenger plane, battery powered with turbine range extender
- Much more efficient, cost effective and quiet than comparable aircraft
- Increase use of small and medium US airports and decrease emissions

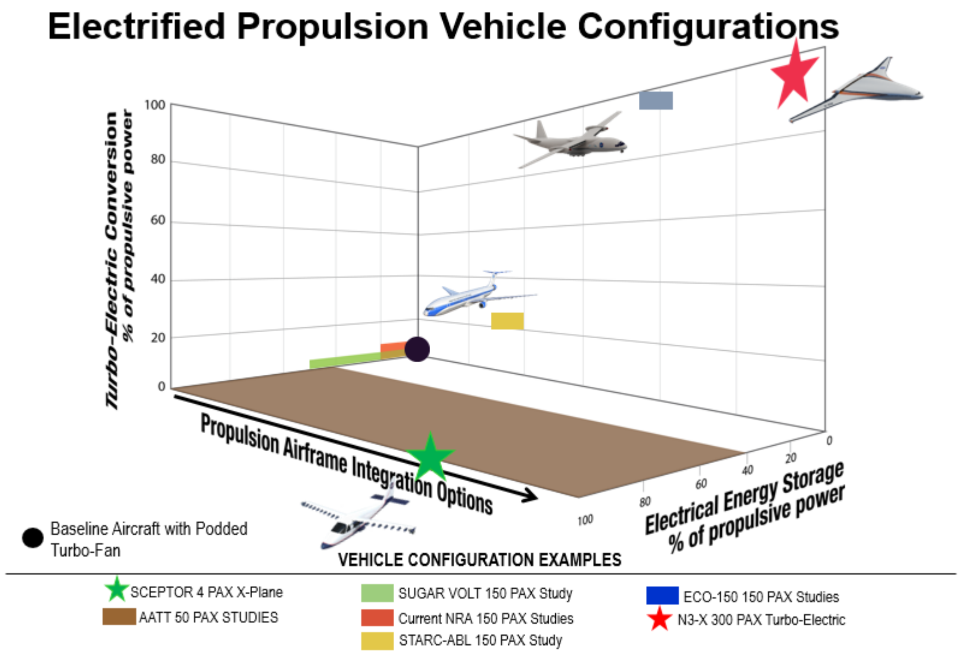
SCEPTOR X-57 Flight Demonstrator

Ground-based testing and Flight Demo for Distributed Electric

- Validate energy use reductions (up to 5X)
- Support projections for reduced operating costs, emissions, noise
- Demonstrate flight controls, power management and distribution, mission profiling, etc.
- Establish certification basis

This talk focuses on Transport Class

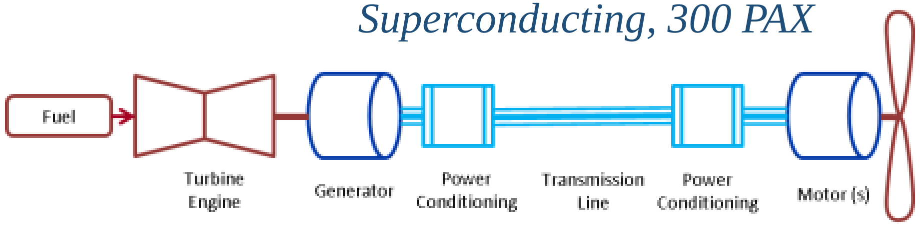
Single-Aisle Electrified Aircraft Design Space



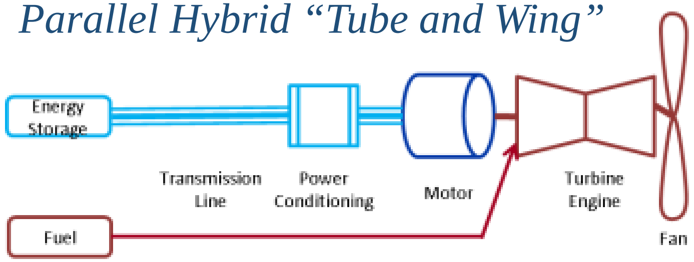
Variations almost unlimited

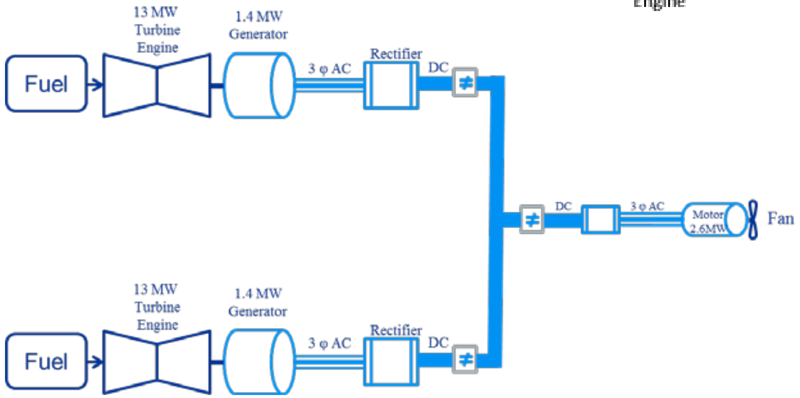
- Number of passengers,
- Transport range
- Assumed performance for new technologies
- Degrees and form of electrification
- ***Currently focusing on three variations***

N3-X
Fully Turboelectric,
Distributed,
Superconducting, 300 PAX



Parallel Hybrid "Tube and Wing"





STARC-ABL
Partially Turboelectric,
Aft Boundary Layer
Ingestion, 150 PAX

Component Technology Investment Method

Baseline Future Vehicle

Predicted Available Technologies

→ Concept that closes w/ Net Benefit

Vehicle Systems Studies including missions profile, propulsion system, CFD

→ Derive Key Powertrain Performance Parameters

Calculated power and efficiency curves, etc.

→ Dissect Contributors to Weight and Loss in SOA

Materials and electromagnetic properties, EMI, fault tolerance, etc.

→ Derive Key Subcomponents Performance Parameters

Concept A

Concept B

…

Build, test, fly, learn at successively higher power and voltage levels

- Validate the vehicle architecture as well as component performance

Investments informed by concepts plus systems-level testbeds

With successively higher fidelity

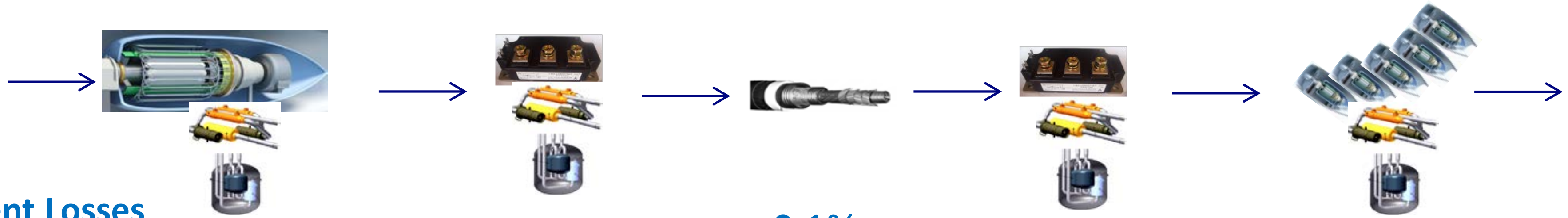
Large, 300 PAX Requires Superconducting

N3-X Aircraft Concept was Used to Focus Component Performance Parameters

- Lower Fan Pressure + Boundary Layer Ingestion
- Superconducting (including transmission)
- ~4 MW Fan Motors at 4500 RPM
- ~30 MW Generators at 6500 RPM
- ~5-10 kV DC Bus Voltages
- End-to-end efficiency of Powertrain = 98%

N3-X
Fully Turboelectric, Distributed, Superconducting, 300 PAX, 7500 nautical miles

Turboelectric Propulsion contributes 9% fuel burn savings (total vehicle net is 70% compared to 2005 baseline)

	Generator	Rectifier	Transmission	Inverters	Motors	
						Cum. Loss 2.1%
Component Losses *Including cryocoolers*	0.45% 50 kW/kg	0.50% 25 kW/kg	0.1%	0.50% 25 kW/kg	0.48% 21 kW/kg	

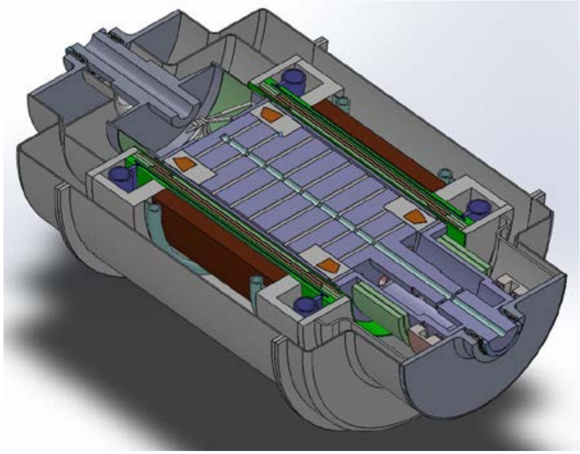
Brown, Weights and Efficiencies of Electric Components of a Turboelectric Aircraft Propulsion System
Armstrong, Rolls Royce North American Technologies, Inc., Architecture, Voltage, and Components for a Turboelectric Distributed Propulsion Electric Grid
GE Aviation, Architecture, Voltage and Components for a Turboelectric Distributed Propulsion Electric Grid (AVC-TeDP)

300 PAX Size Class Technology Development Goals

Key Performance Goals for Superconducting Systems

Derived from N3-X and related studies

- Near-term challenge is to design a MW-class, fully superconducting electric machine with:
  - 4 MW >16.4 kW/kg
  - 4,000 RPM >99% efficient
- Address issues with stator coil
  - Understand and reduce AC losses in wire
  - Medium temperature (20°K) superconducting coils
  - Manufacturability
- Advanced cryocoolers
- Cryogenic Power Converters
  - 17-35 kW/kg >99.0 % efficient



Model and Design of a Fully Superconducting Electric Generator for Novel Aircraft Propulsion Applications G. Brown, J. Trudell (GRC) P. Masson (AML)

Fully Superconducting Machine Details

Required Power - - - - - - - -	1 to 30 MW
Required Speed - - - - - - - -	2,000 to 12,000 rpm
Number of pole pairs - - - - - -	2 to 4
Number of phases - - - - - - -	3 or more
SC* type and properties range	
Material - - - - - - - - - -	BSCCO, YBCO, MgB_2
Temperature - - - - - - -	20 to 77 K
Magnetic field - - - - - -	0.2 to 2.5 T
SC wire parameters	
SC filament diameter - -	5 to 100 µm
Twist pitch - - - - - - -	0.5 to 10 cm
Wire diameter - - - - - -	0.2 to 2.0 mm
Material properties	
Metals - - - - - - - - - -	Al, Ti, Inconel, 304 S.S.
Composites - - - - - - - -	G10CR, various

SC: superconductor
BSCCO: barium strontium calcium copper oxide
YBCO: yttrium barium copper oxide
MgB_2: magnesium diboride

150 PAX Narrow Body Offers Nearer-term Options

Boeing Research & Technology, Boeing N+3 Subsonic Ultra Green Aircraft Research (SUGAR) Final Report

Welstead, Felder, Conceptual Design of a Single-Aisle Turboelectric Commercial Transport with Fuselage Boundary Layer Ingestion

Boeing SUGAR Volt
- Parallel hybrid, ~150 PAX
- 750 kW/kg batteries charged from green grid
- 1-5 MW, 3-5 kW/kg, 93% efficient electric machines
- 60% efficiency improvement over 2005 baseline aircraft if a renewable grid is assumed (i.e. wind) to charge batteries

Detailed Parallel Hybrid Analyses
- Looked further into mission optimization
- Rolls Royce
- United Technologies Research Center

STARC-ABL
- Single aisle, turboelectric (partially), 150 PAX
- Aft boundary ingesting electric motor (lightly distributed)
- 2.6 MW motor, ~2500 RPM
- 1.4 MW generator, ~7000 RPM
- 13.6 kW/kg, 96% efficient electric machines
- 7-12% fuel burn savings for 1300 nm mission

Parallel Hybrid and STARC-ABL common themes

Concepts and Other Studies Expose Universal Needs

Energy Storage	Electrical Distribution	Turbine Integration	Aircraft Integration
Battery Energy Density	High Voltage Distribution	Fan Operability with different shaft control	Stowing fuel, stowing & swapping batteries
Battery System Cooling	Thermal Mgt. of low quality heat	Small Core development and control	Aft propulsor design & integration
	Power/Fault Management	Mech. Integration	Integrated Controls
	Machine Efficiency & Power	Hi Power Extraction	
	Robust Power Electronics		

Legend		
Parallel Hybrid Specific	**Common to Both**	**Turboelectric Specific**

Component Technology Investment Strategy

- Targeting common themes for powertrain
- Invest first in flightweight motors, generators and power electronics
- Successively include more interfaces (motor plus controller, filter, thermal control, etc.)
- Enabling materials to achieve required power, voltage, energy densities and efficiencies

Targeted Higher Risk Work

- Multifunctional structures (structure integrated with battery/supercapacitor)
- Electrolyte engineering for lithium-air batteries
- Variable frequency AC, high voltage (kV) transmission with double fed induction machines
- Additive manufacturing for electric machines

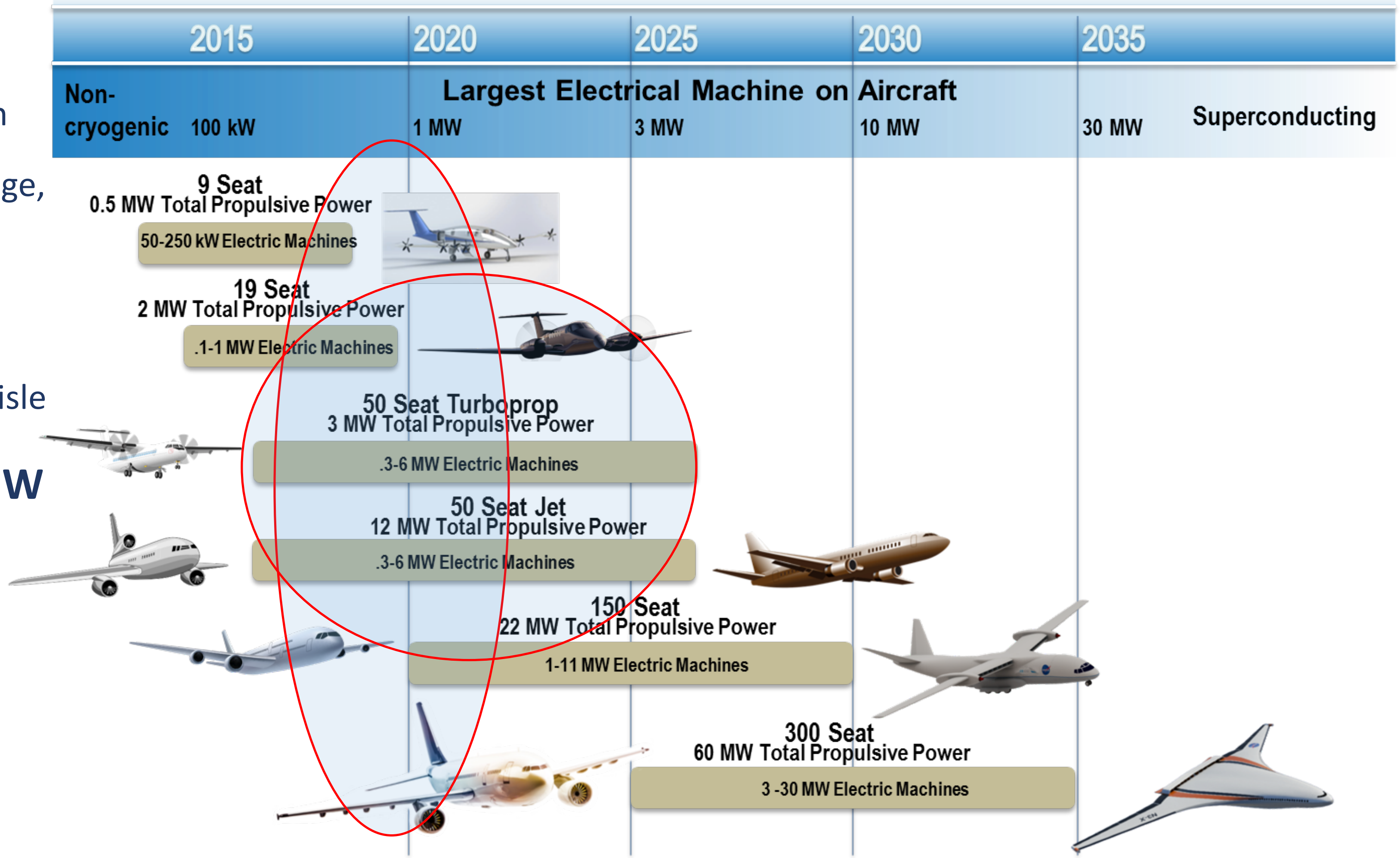
Power Requirements for Electric Machines

Electric machines required for selected electrified aircraft shown

- Total electric power used for propulsion
- Range of motor and generator sizes used in each configuration
- Up to 150 passengers can get away with MW range, traditional cooling
- Largest of the concepts require cryogens to get superconducting performance
- 1 MW class of machines common to majority of concepts NASA is looking at
- Benefit smaller transport class as well as single aisle

Near-term Challenge is to focus on 1-3 MW powertrains with MW-class components

- Electric Motors and Generators
  - 1-3 MW >13 kW/kg
  - >96% efficient ~2500-7000 RPM
- Power Converters (rectifiers, inverters)
  - >1 kV DC bus 3ϕ AC
  - >12-25 kW/kg >98% efficient



PS–01758–1115

Impact of Materials on Electrical Machine Performance

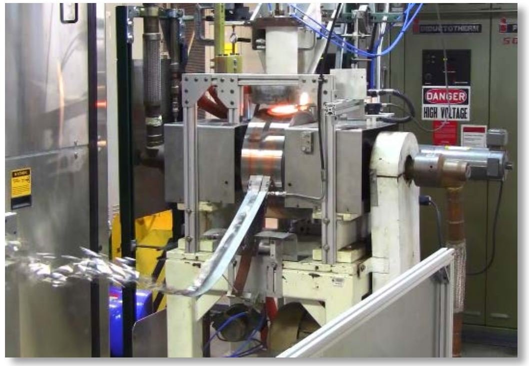
Electromagnetic Finite Element Analysis Conducted

- Identified sensitivity of Power Density and Efficiency to differing material property improvements
- Four machine types for two drive conditions, common dimensions)

Materials Technologies Studied

- Improved dielectrics and insulation
- Carbon nanotube/Copper composites to increase conductivity
- Nanocrystaline magnetic materials to enable high frequency circuit devices

50% reduction in loss at high frequency



Bowman, R, Noebe, R, NASA Pilot-Scale Amorphous Ribbon Caster

Drive	Motor Type	Baseline Materials: Power Density kW/kg (HP/lb)	Baseline Materials: Efficiency	Improved Materials: Power Density kW/kg (HP/lb)	Improved Materials: Efficiency
Standard	SPM	10.6 (6.4)	95.1%	14.5 (8.8)	97.4%
	IPM	10.4 (6.3)	96.6%	14.0 (8.5)	98.3%
	SRM	4.6 (2.8)	93.5%	4.9 (3.0)	97.1%
	IM	3.5 (2.1)	94.8%	4.9 (3.0)	97.6%
Tip Drive	SPM	9.6 (5.8)	90.9%	12.0 (7.3)	93.3%
	IPM	9.8 (6.0)	96.5%	12.0 (7.3)	97.7%
	SRM	8.7 (5.3)	96.4%	9.6 (5.8)	98.3%

K. Duffy, Electric Motors for Non-Cryogenic Hybrid Electric Propulsion (AIAA 2015-3891)

1. Surface-mounted permanent magnet (SPM)
2. Interior permanent magnet (IPM)
3. Synchronous reluctance motors (SRM)
4. Induction Motors (IM)

Modeling, Analysis and Simulation for Concept Validation

High Fidelity CFD using rapid techniques

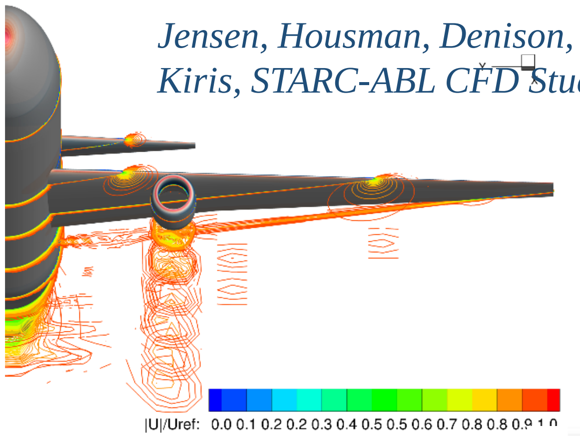
- Critical for designs where propulsion and airframe are highly coupled
- Refine and optimize concepts (shape tail, nacelle, attachment points, etc.)
- Viscous simulation to study boundary layer
- Adaptive mesh provides for rapid iterations between airplane shape and predicted propulsive benefits

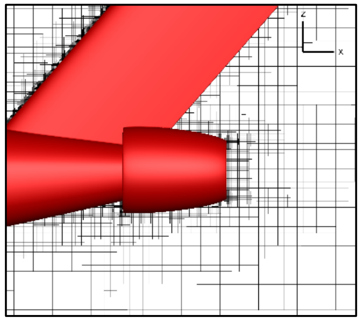
Dynamic Modeling

- Electrified aircraft have increased steady-state and peak (transient) cooling and power requirements, nonlinear transient loads
- Developing virtual testbed using Distributed Heterogeneous Simulation[1] (computationally efficient, integrated system simulations with protection of proprietary data)
- Using Air Force Research Lab (AFRL)'s INVENT Modeling Requirement and Implementation Plan (MRIP) platform

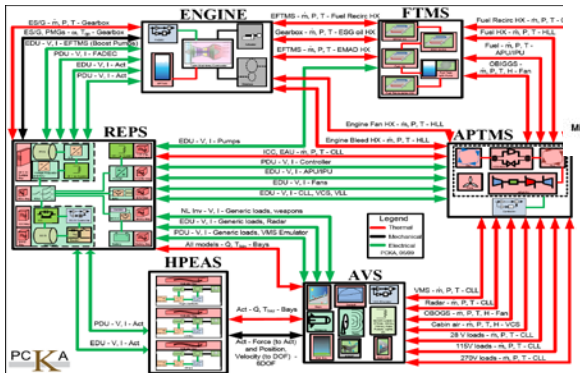
Piloted Simulations and Controls Research

- Performance and control research and testing in preparation for flight demonstrators
- Validate ideas such as hybrid power sharing, windmilling, battery start
- Lessons and scalability for larger MW-scale architectures

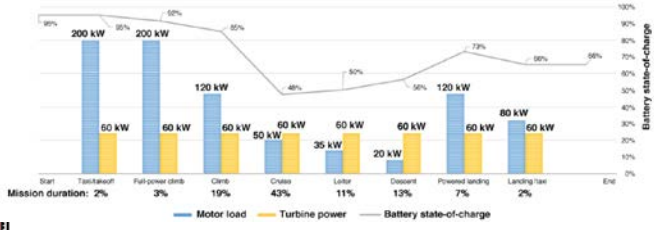




Jensen, Housman, Denison, Barad, Kiris, STARC-ABL CFD Studies,



AFRL INVENT MRIP, Cleared for public release, 88ABW-2011-4647, 26Aug11



Papathakis et. al., Design and Development of a 200-kW Turbo-electric Distributed Propulsion Testbed

1. PC Krause and Associates, Inc.

Risk Reduction Enabled by Integrated Systems Testbed

Full aircraft and mission ground simulation at 200 kW scale in HEIST

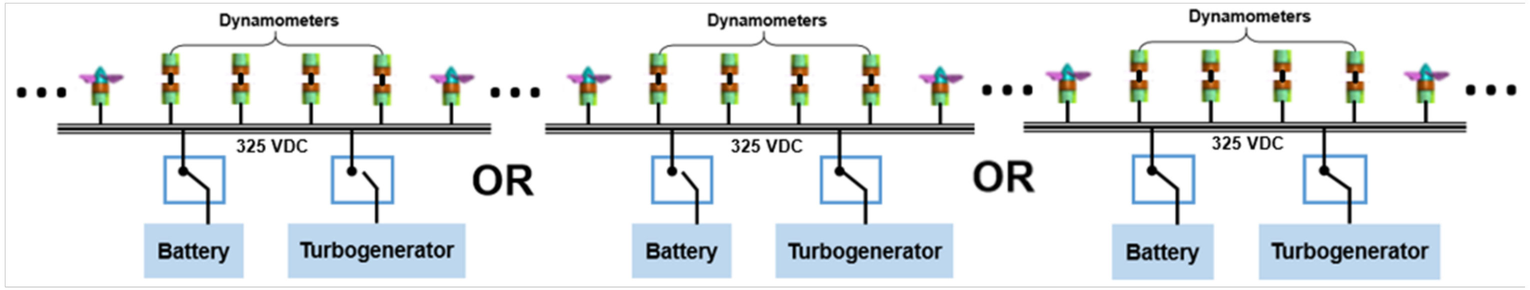
- Distributed propulsion along wing
- Turbogenerator or batteries (or both)
- Integrated with flight simulator and cockpit
- Can emulate failure scenarios
- Aerodynamic feedback via dynamometers

Full-scale Powertrain Testing at NEAT

- 1-10’s MW, reconfigurable testbed
- Validate that powertrain is still flightweight and efficient with all systems interacting
- Include thermal, electromagnetic and fault controls
- Study bus stability with different power source, varying loads, and mixing of cryogenic systems with ambient

HEIST: Hybrid Electric Integrated Systems Testbed

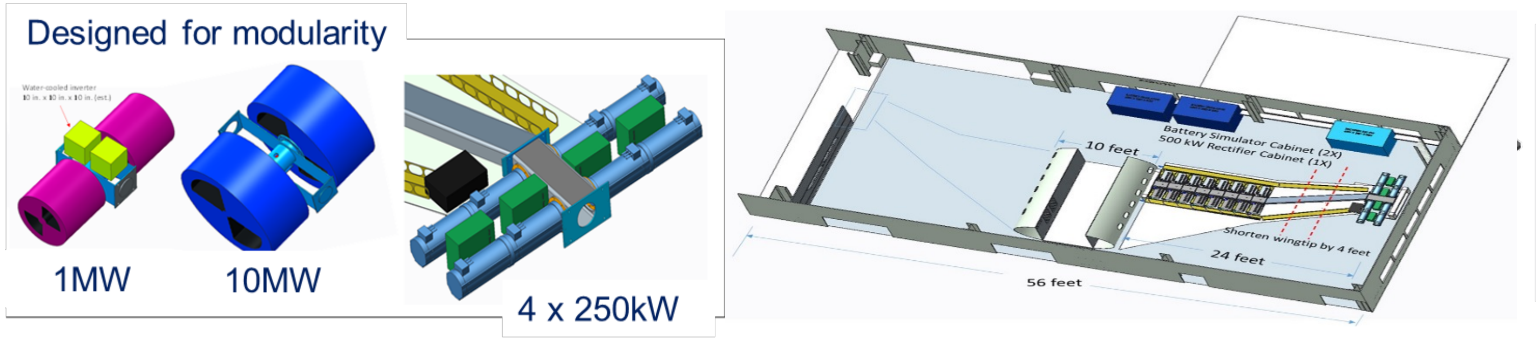
Flight controls integrated with Electrified Aircraft Hardware in the Loop



Battery Powered | **Turbine Powered** | **Hybrid Power Sharing**

NEAT: NASA Electric Aircraft Testbed

High power ambient and cryogenic flight-weight power system testing




We are looking forward to developing technologies, studying airplane architectures and controls, and helping to pave a way forward for electrified planes in the US airspace